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DESIGN AND ANALYSIS OF SOLID PROPELLANT ROCKET NOZZLE AND ITS APPLICATIONS TO RCS

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ABSTRACT

Design of a Solid Rocket Nozzle as well as the Computational Study of Flow Analysis through Nozzle will be carried in the Present Project by accelerating exhaust gases at very high-speed rocket engines generates Thrust. Nozzle Design is a multi-objective approach as it depends on various factors and plays an important role in the whole performance of the Rocket. After reaching certain altitude, it is very difficult to Control and Stabilize the Rocket using control surfaces due to the absence of atmosphere. So, our aim is to Design the Nozzle which can be applicable for the Reaction Control System (RCS), which is the mechanism used in rockets for controlling in the absence of Atmosphere. For this purpose, initially the Design Procedure, Design Aspects and the Performance of Nozzle with respect to Altitude will be studied and then Ideal Rocket Nozzle will be designed which can operate successfully at high altitudes.

KEYWORDS: Reaction Control System (RCS), Design, Flow Analysis, Altitude & Ideal Rocket Nozzle

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Original Article

1. INTRODUCTION

Newton's laws, force is directly proportional to rate of change of momentum and action and reaction are equal and opposite in nature. Aerospace propulsion system is best example for obeying these laws.

By accelerating exhaust gasses at very high-speed Rockets will generate thrust. These exhaust gasses will generate in combustion chamber by burning propellant, either solid or liquid. At a very high-speed gasses generated in combustion chamber will pass through Nozzle. Shape of Nozzle depends on Rocket size and exhaust gas velocity.

Rocket Nozzle usually divided into three parts, which are Converging Section, throat and Diverging section. Gasses from combustion chamber will enter into Converging section where gasses move at subsonic speeds, to increase the velocity gasses will move through throat where gasses will achieve supersonic speed at Diverging section of Nozzle.

A converging-diverging (CD) nozzle is a nozzle that accelerates a fluid to supersonic speeds (speeds greater than the speed of sound through that fluid). In order to fully understand what this means each piece should be broken down and defined itself. The final picture will become clearer as the pieces are put together.

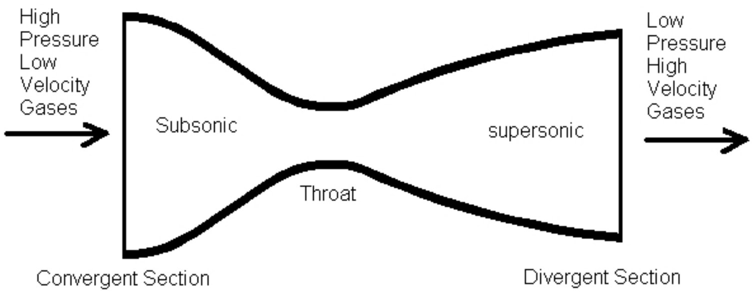

Figure 1.1: Convergent-Divergent Nozzle Section

1.1 Reaction Control System for Re-Entry Vehicles (RCS)

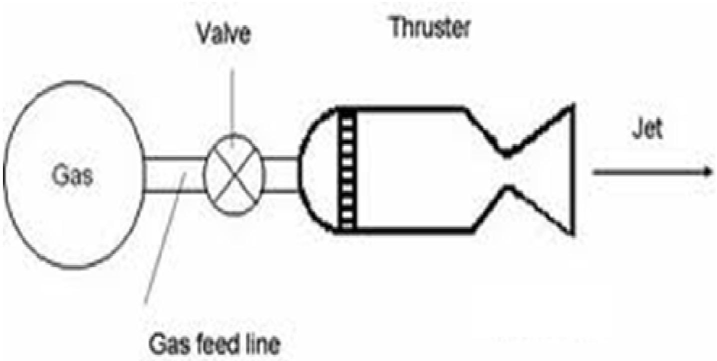

Figure 1.2: Block Diagram of Reaction Control Thrusters

RCS is used to provide control on re-entry vehicle in the absence of aerodynamic forces. The RCS system stabilizes the vehicle on roll, pitch and yaw. RCS is a subsystem of a spacecraft/re-entry vehicle/ missile. Its purpose is to provide attitude control and steering. The attitude control system functions to maintain the re-entry vehicle in the desired attitude on the ordered flight path by controlling the vehicle manoeuvres (pitch, roll, and yaw). The attitude control system operates as an auto pilot, damping out fluctuations that tend to deviate the re-entry vehicle from its desired path. The operation of a guidance and control system is based on the principle of feedback. A reaction control system (RCS) system can provide required thrust in any desired direction or combination of directions. The RCS is also capable of providing torque to allow control of roll. This contrasts with a main engine of ballistic missile, which is only capable of providing thrust in one direction but is much more powerful.

2. METHODOLOGY

- **Aim and Objective**

Aim: To Design a Nozzle for an ideal rocket that has to operate at high altitude having the targeted Thrust and then usage of the designed nozzle for Reaction Control Systems as well as to do the Performance study of the nozzle with respect to Altitude followed by Flow Analysis using Software's.

Objective: The Main Objective of the project are the following.

- Design of Nozzle using Analytical method
- Study of characteristics of Nozzle for various operating conditions
- Flow analysis of axisymmetric using CFD
- Application to Reaction Control System(RCS)

- **Project Layout**

This study involves the design and analysis of a rocket Nozzle, initially it will start with Design of Nozzle using Analytical method followed by Study of characteristics of Nozzle for various operating conditions, Flow analysis of axisymmetric using CFD and Application to Reaction Control System (RCS).

Software's going to be used in this thesis is CATIA for modeling the object and then continued in ANSYS Workbench for Meshing and for Flow analysis followed by dynamic analysis. After obtaining thrust coefficient over the body Normal force is going to be calculated using Numerical calculations.

- **Inference from Literature Survey**

The aim of any project is to report the new results in scientific journals to spread the information to across the world for new inventions. As many journals are available for more than one source, the literature survey done for the process of designing of nozzle for solid propellant rocket also is wide. This project involves the Design the Nozzle which can be applicable for the Reaction Control System (RCS), which is the mechanism used in rockets for controlling in the absence of Atmosphere.

- **Motivation to Work**

A nozzle design theory is only involving the Method of Characteristics, a very lengthy and confusing procedure and designing of a rocket nozzle operates at high altitude isn't so easy. As the theoretical procedure is involved less, which made a path for choosing of analytical procedure involved in the books for designing of ideal nozzle for small rocket model and performing the flow analysis through it, finally use this nozzle for Reaction Control Thrusters, which can operate at an altitude of 30km from sea-level.

3. MODELING AND NUMERICAL CALCULATIONS

3.1 Geometry Modeling

CATIA is chosen for modeling the Rocket Nozzle. A 2-D nozzle has been designed in using CATIA and analysis has been done on the same. Design consideration is taken in such a way that Chamber contraction ratio varies from 3 to 6 based on Chamber Pressure to atmospheric pressure ratio to find the are of Nozzle inlet. Angles taken are 30 and 15 degrees at Inlet and out let of nozzle respectively.

The below figure represents longitudinal section of a converging-diverging nozzle symmetric about the axis. Nozzle length (L) is 0.31 m. The inlet radius (r1) and outlet radius is considered as 0.0178 m and 0.082 m respectively. The half cone angle for the diverging section is $15^0$and the half cone angle for the converging section is 30^0. The pressure across the nozzle inlet is 2 MPa.

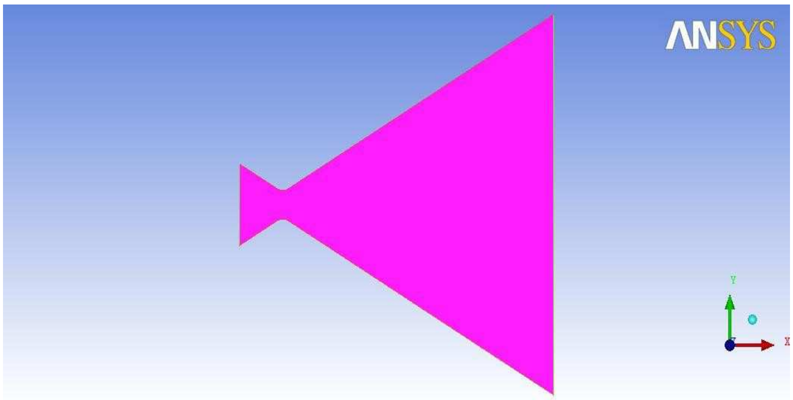

Figure 3.1: Domain of Nozzle in CATIA

Selection of Propellant

Double-Base (DB) Solid Propellant has chosen for our Project because of the following reasons.

- Homogeneous propellant grain usually Nitroglycerin dipped in Nitrocellulose
- Smokeless exhaust

- Currently using in wide range of applications
- It is possible to improve the performance as well as Specific Impulse slightly by adding some ingredients
- Potentially detonable and Less toxicity

And the Characteristics of this propellant are,

- Specific Impulse: I_{sp} = 220-230sec
- Flame Temperature: T_c = 2550k
- Burning Rate: r = 0.05 to 1.2 in/sec
- Pressure Exponent: n = 0.3
- Empirical Constant a = 0.06

3.2 Design Aspect

There are a few very key components to designing an effective CD nozzle. The first is what size to make the throat, the thinnest part of the nozzle. This is important because the size of the throat will determine how large the mass flow rate can get before the nozzle becomes choked. In this way, the size of the throat effectively sets the mass flow rate through the nozzle. Next, the area of the exit is important because it will determine how much the fluid can expand. This expansion will then determine the Mach number of the exiting flow. It also determines the exit pressure, temperature, and velocity of fluid coming out. So, in order to control how much mass is moving and how fast it moves, the ratio of the exit to the throat is the key design component.

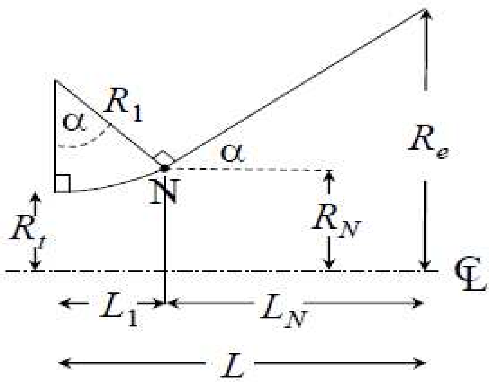

Figure 3.2

3.3 Flow Analysis

Flow Analysis has been performed with the use of Software CFD which stands for Computational Fluid Dynamics. Below is the Nozzle Model which shows the Mesh of Nozzle designed.

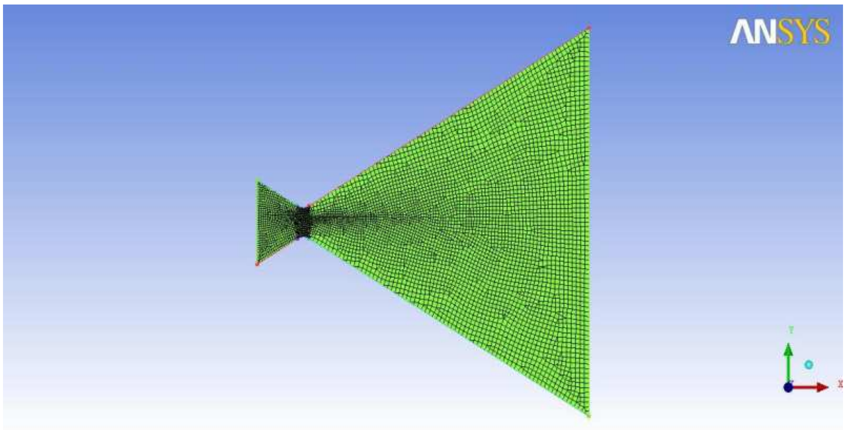

Figure 3.3: Meshed Nozzle

Once the boundary condition has set the values defined for generating results are as followed.

The Pressure at Inlet panel opens values are Gauge Total Pressure as 2000000 Pascal, Supersonic/Initial Gauge Pressure as 2000000 Pascal, Total Temperature is set to 300 K, values of Turbulence Intensity and Hydraulic diameter as 2% and 0.17 respectively. For higher Reynolds number flow, turbulent intensity is in the range of 1-5%. In this case, set it to 2% as the diameter of inlet is 0.17 m. Set the hydraulic diameter to 0.2 m.

The Pressure Outlet Panel opens values are Gauge Pressure as 1197 Pa (at 30km altitude) or 0.1013MPa (at Sea level). The outlet is assumed to open in the atmosphere. So the outlet pressure is set approximately equal to the atmospheric pressure. Backflow Total Temperature (k) is set to 300. Turbulence Intensity and Hydraulic diameter as 2 and 0.8 respectively.

3.4 Contours of Static Pressure as Follows

If we have a close look at below diagrams it clearly shows the difference between the Nozzle performances at 30km altitude and at Sea level.

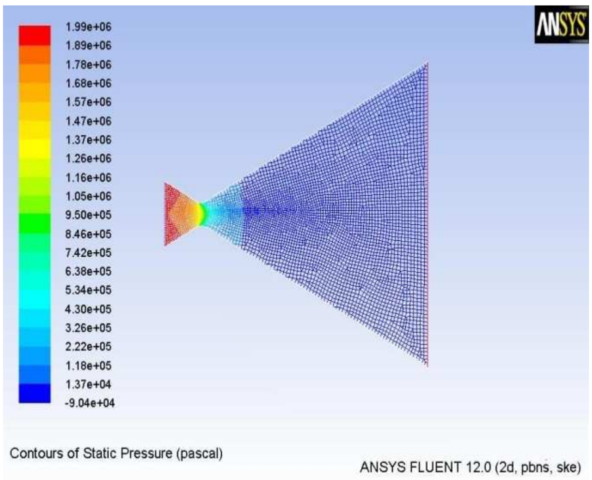

Figure 3.4: Contours of Static Pressure at 30 km

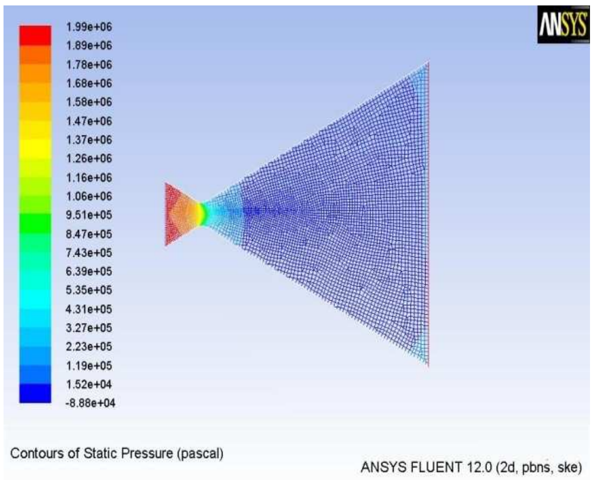

Figure 3.5: Contours of Static Pressure at Sea Level

3.5 Contours of Velocity Magnitude as Follows

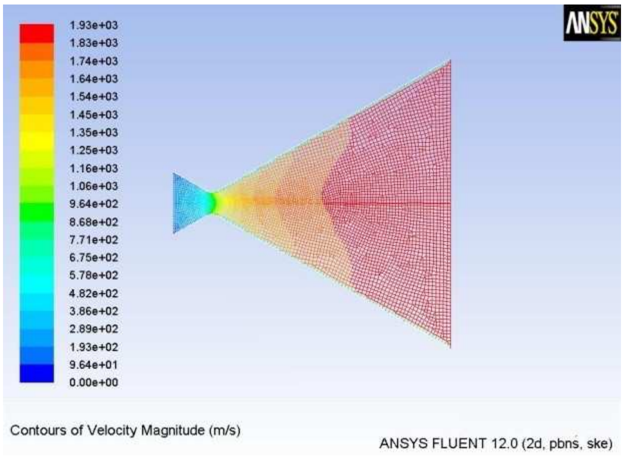

Figure 3.6: Contours of Velocity Magnitude at 30 km

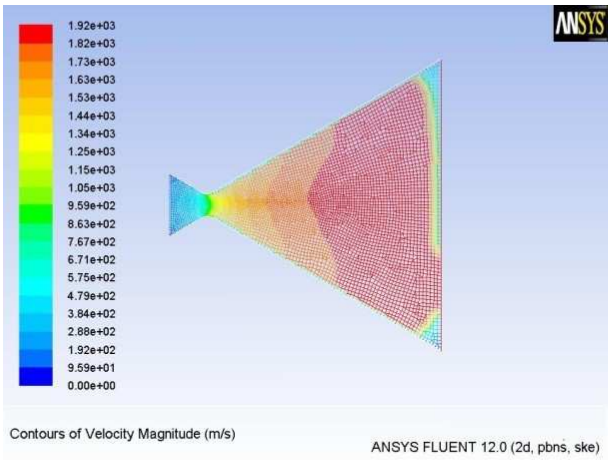

Figure 3.7: Contours of 'v' at Sea Level

3.6 Static Structural Analysis

In performing the Analysis of the Nozzle, we need to perform few tasks, irrespective of the tools we are using we must complete below tasks like, Generating Mesh, Material Properties Assignment, Defining Analysis type, Setting up boundary conditions, Solve and Reviewing results.

Below are the results of the nozzle after generating Mesh and counter of Mach Number

The residuals plot is shown in figures at 30 km altitude and Sea level respectively.

The Static Pressure is shown in figures at 30 km altitude and Sea level respectively.

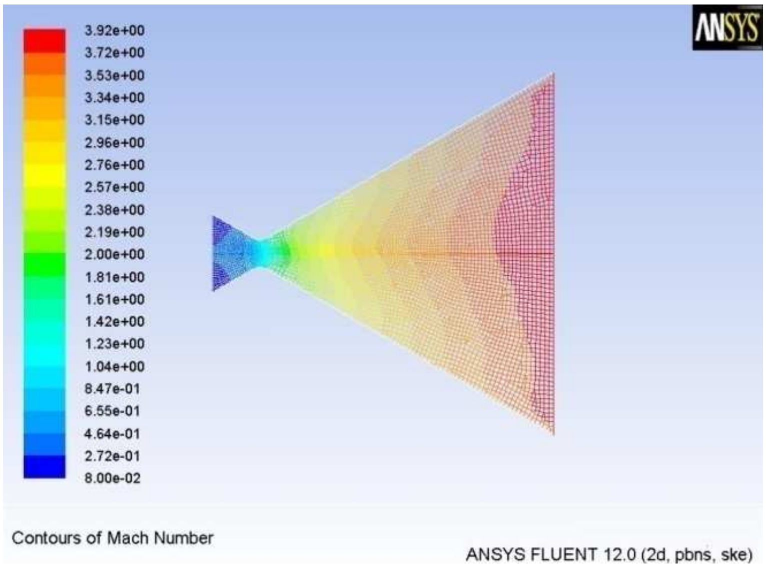

Figure 3.8: Contours of Mach Number

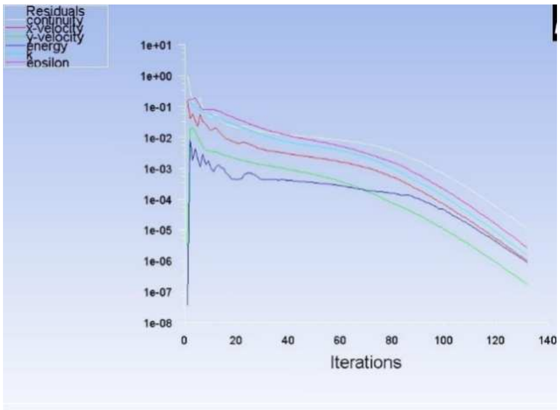

Figure 3.9: Scaled Residuals at 30 km Altitude

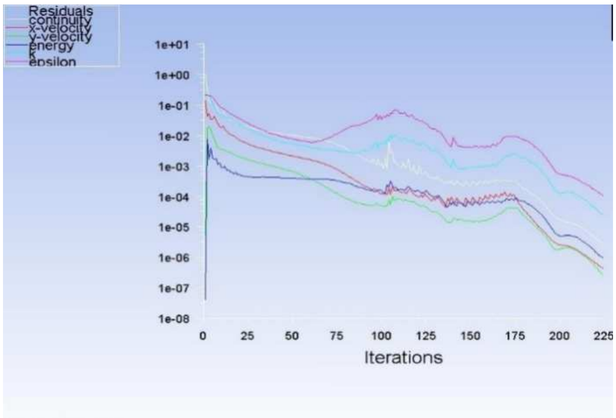

Figure 3.10: Scaled Residuals at Sea Level

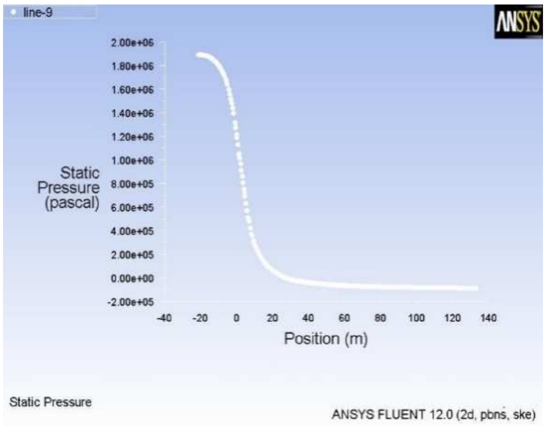

Figure 3.11: Static Pressure at 30 km

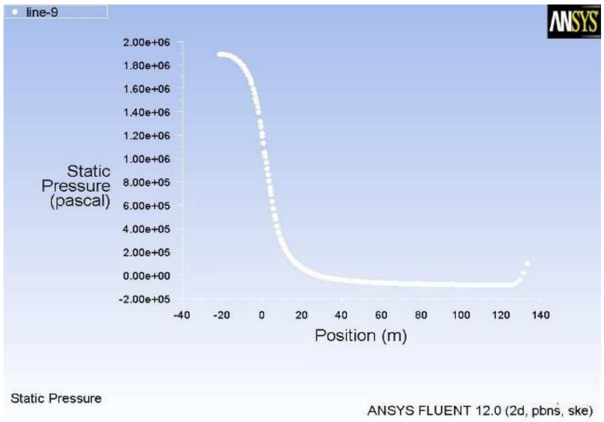

Figure 3.12: Static Pressure at Sea Level

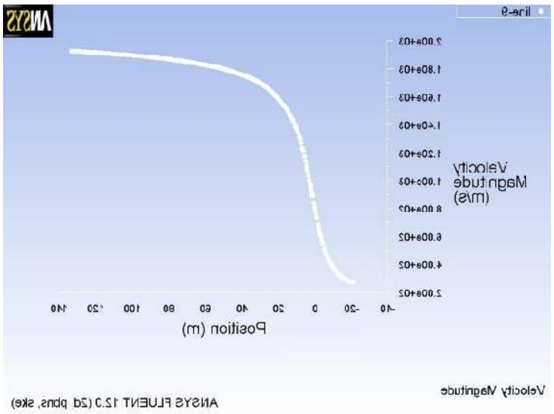

Figure 3.13: Graph for Velocity at 30 km

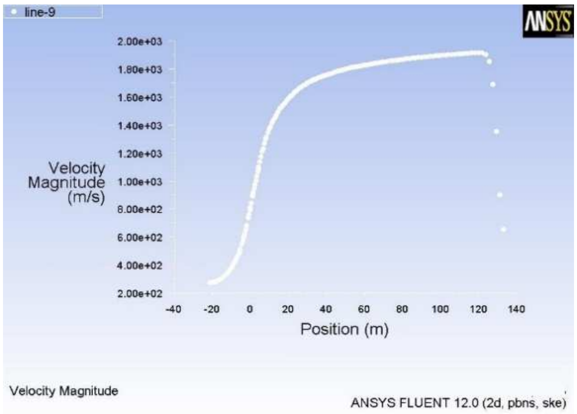

Figure 3.14: Graph for Velocity at Sea Level

The Velocity is shown in figures at 30 km altitude and Sea level respectively.

- **Numerical Calculations**
  - Assumptions: k=1.3 R=355.4 J/kg-k
  - We know that. $r = a \times p^n$
    - here 'r' varies from 0005 to 1.2 in/sec and n=0.3, a=0.06

    Therefore:- Pmax = 21,715.34 Psia = 149.727 Mpa

Pmin = 0.54458 Psia = 0.00375 Mpa

- Select P_1 = 2.068 MPa
- At 30 km altitude: P_3 = 1197 N/m^2 = 0.001197 Mpa
- Pressure ratio = $P_2/P_1 = P_3/P_1$ = 0.00057882
- Critical Pressure: $P_t = P_1\left(\frac{2}{k\_1}\right)^{\frac{k}{k-1}}$ = 1.1286 MPa
- Throat Velocity: $V_t = \sqrt{\frac{2KRT_1}{k+1}}$ = 1012.165 m/s
- Ideal exit Velocity: $V_2 = \left(\frac{2kRT_1}{k-1}\right) \times \left\{1 - \left(\frac{P_2}{P_1}\right)^{\left(\frac{K-1}{K}\right)}\right\}$ = 2539.346 m/s
- Propellant Consumption: $\dot{m} = \frac{F}{V_2}$ = 0.386 kg/sec
- Specific Volume at the nozzle entrance: $v_1 = \frac{RT_1}{P_1}$ = 0.438 m^3/kg
- Specific Volume at the nozzle throat: $v_t = v_1 \times \left(\frac{k+1}{2}\right)^{\left(\frac{1}{k-1}\right)}$ = 0.698 m^3/kg
- Specific Volume at the nozzle exit: $v_2 = v_1 \times \left(\frac{P_1}{P_2}\right)^{\left(\frac{1}{k}\right)}$ = 135.464 m^3/kg
- Therefore, Areas:-

$$A_t = \dot{m} \times \frac{v_t}{V_t} = 0.000266 \text{ m}^2 = 2.66 \text{ cm}^2$$

$$A_2 = \dot{m} \times \frac{v_2}{V_2} = 0.02059 \text{ m}^2 = 205.92 \text{ cm}^2$$

- Area Ratio: $\varepsilon = \frac{A_2}{A_t}$ = 77.4
- $T_2 = T_1 \times \left(\frac{P_2}{P_1}\right)^{\left(\frac{K-1}{K}\right)}$ = 456.494 K
- Finally, Thrust Coefficient: $C_f = \frac{F}{(A_t \times P_1)}$ = 1.78
- **Note:** Thrust Coefficient is the important Design Parameter, here it decides whether the Procedure carried and values obtained above are correct or not by comparing above C_f with the Theoretical C_f value which is a function of Pressure Ratio (P_1/P_2=1727.65), Area Ratio ($\varepsilon = A_2/A_t$ = 77.4) and Ratio of Specific heats (k=1.3) as shown in the bellow figure.

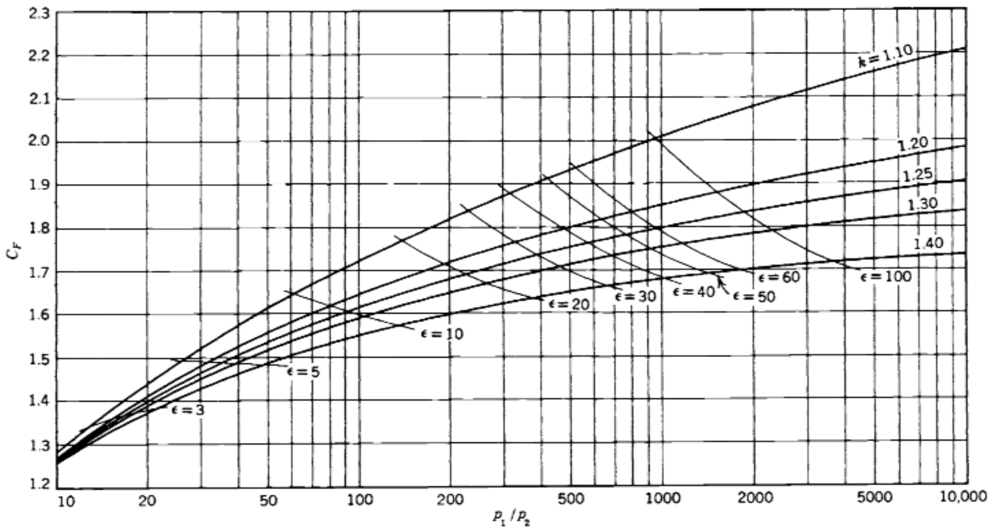

Figure 3.15: Variation of C_f with Respect to Pressure Ratio, Area Ratio & Ratio of Specific Heats

- Finally, Theoretical C_f = 1.75 – 1.80
- Calculated C_f = 1.78
- Hence, the Calculations and Procedure followed above is true.
- Thus, Chamber to Throat Area ratio selected from the below table $\varepsilon_c = \frac{A_c}{A_t}$= 3.5
- Therefore, $A_c = 3.5 \times 2.81156$ = 9.84.46 cm^2

Variation in Nozzle Dimensions With Respect to Chamber Pressure

Table 1

Design Chamber(Pc)-Mpa	(Pt)-Mpa	(Vt)-m/s	(Ve)-m/s	(mdot)-kg/sec	(At)-cm^2	(Ae)-cm^2	(Ar)	Cf
2.068	1.12856	1012.17	2539.346	0.3938	2.71681	210.191	77.3668	1.77988

Performance of the Nozzle at Sea Level

The Performance of Nozzle as per the specifications obtained above can be calculated by following below procedure.

- At Sea level: Atmospheric Pressure P_3 = 0.1013 MPa
- Chamber Pressure: P_1 = 2.068 MPa
- Chamber Temperature: T_1 = 2550 k
- Propellant mass flow rate: $\dot{m}$ = 0.386 kg/sec
- k = 1.3
- R = 355.4 J/kg-K

- Specific Volume at the nozzle entrance: $v_1 = \frac{RT_1}{P_1}$ = 0.438 m^3/kg
- Exit Velocity: $V_2 = \left(\frac{2KRT_1}{K-1}\right) \times \left\{1 - \left(\frac{P_2}{P_1}\right)^{\left(\frac{K-1}{K}\right)}\right\}$ = 1984.587 m/s
- Thrust at Sea level: $F = \dot{m} \times V_2$ = 766.05 N

4. RESULTS AND DISCUSSIONS

After reaching a certain altitude, it's almost impossible to Control and Stabilize the Rocket using Control Surfaces because of atmosphere absence. So, a Nozzle been designed using which we can control rocket and applicable to Reaction Control System as well. Initially Normal force values are calculated and compared.

The Analysis for the Converging- Diverging Nozzle at the 30 km are as Follows

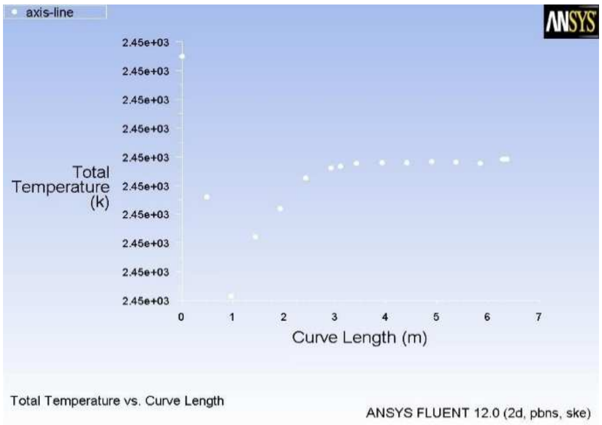

Figure 4.1: Total Temperature Vs Curve Length

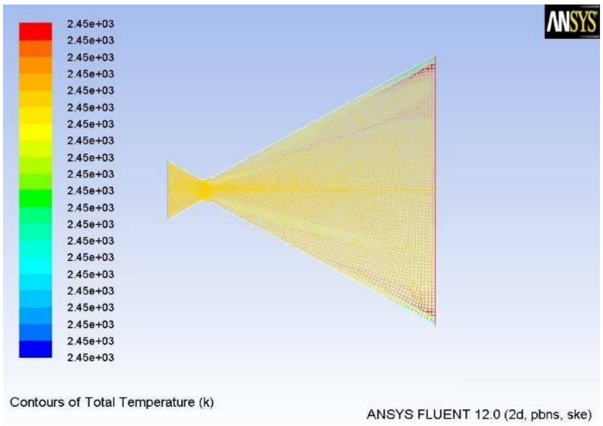

Figure 4.2: Contours of Total Temperature

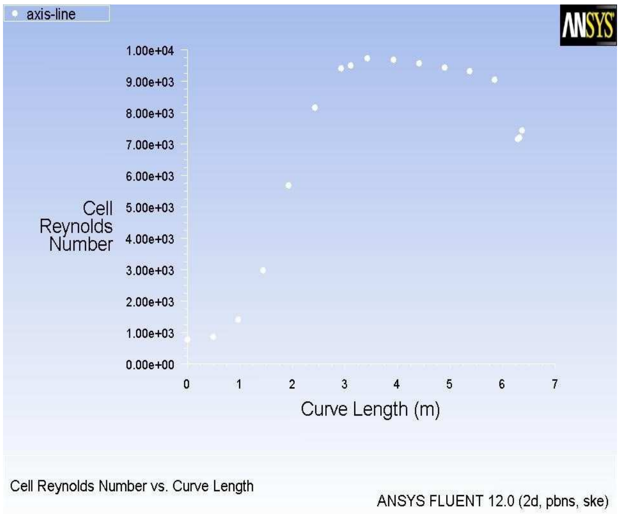

Figure 4.3: Cell Reynolds Number Vs Curved Length

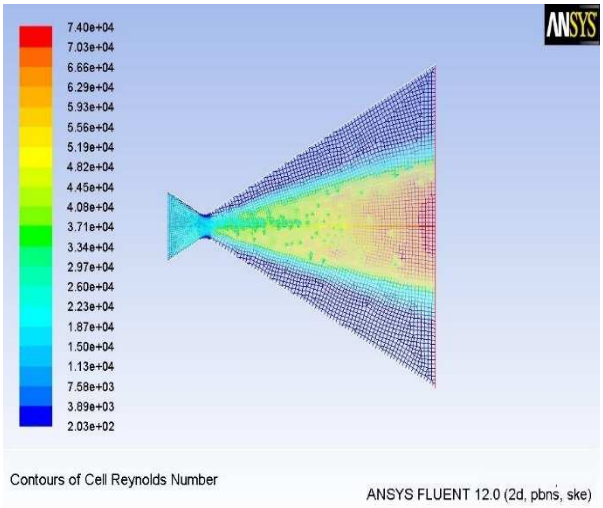

Figure 4.4: Contours of Cell Reynolds Number

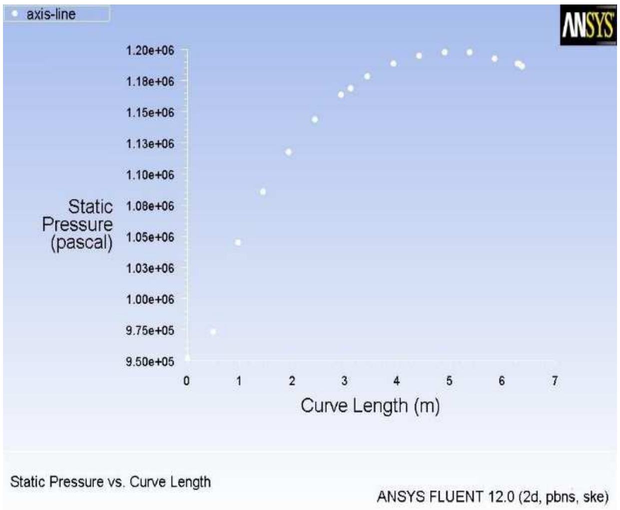

Figure 4.5: Static Pressure Vs Curved Length

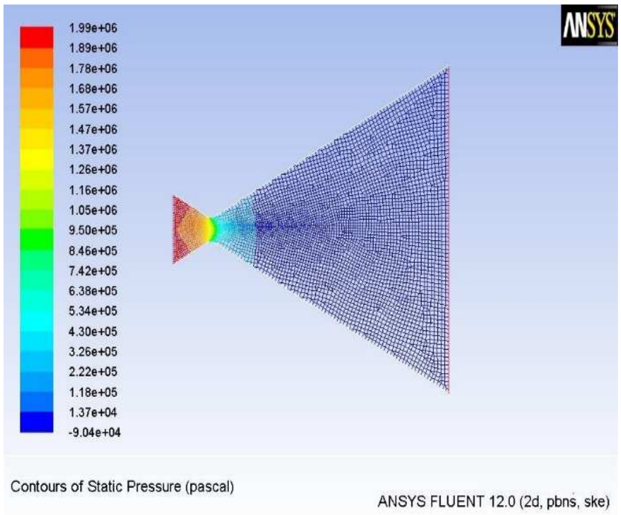

Figure 4.6:: Contours of Static Pressure

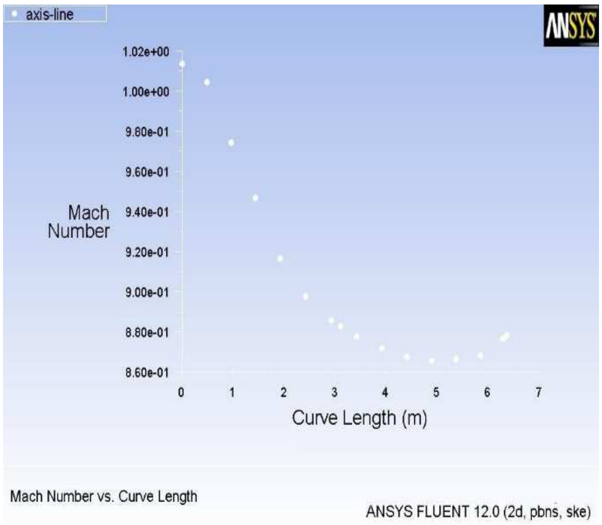

Figure 4.7: Mach Number Vs Curved Length

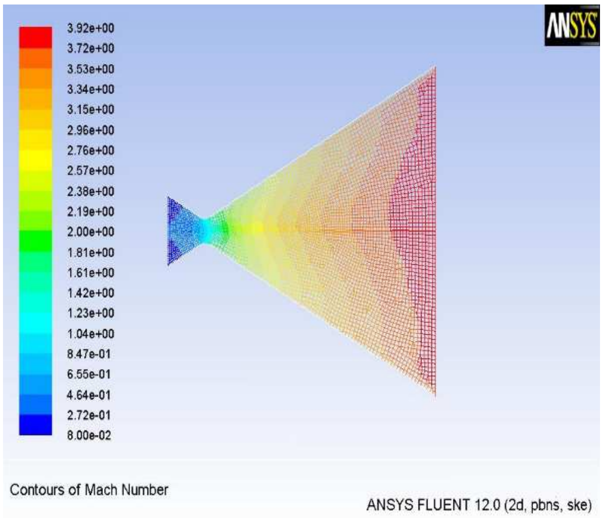

Figure 4.8: Contours of Mach Number

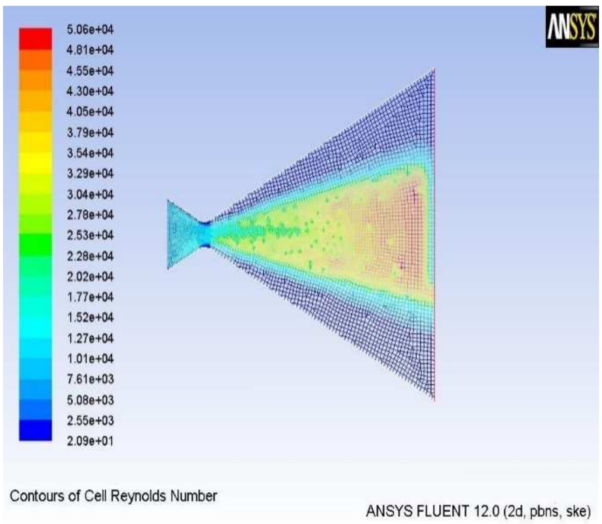

Figure 4.9: Contours of Cell Reynolds Number

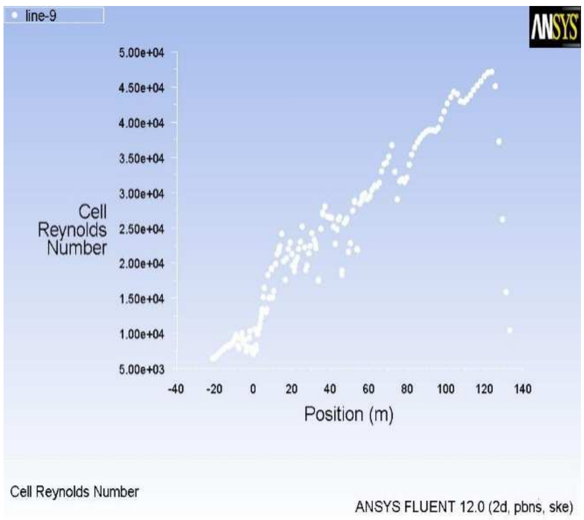

Figure 4.10: Cell Reynolds Number vs Position

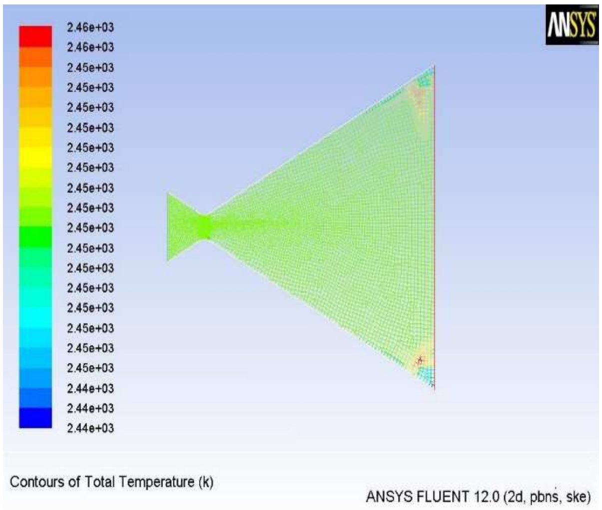

Figure 4.11: Contours of Total Temperature

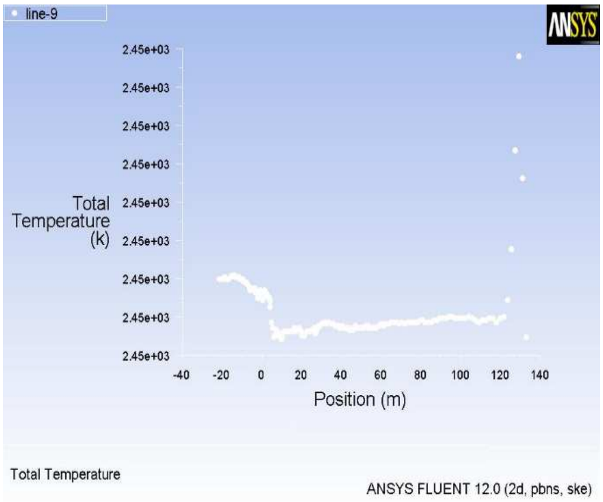

Figure 4.11: Total Temperature Vs Position

The Analysis for the Converging- Diverging Nozzle at the Sea Level are as Follows

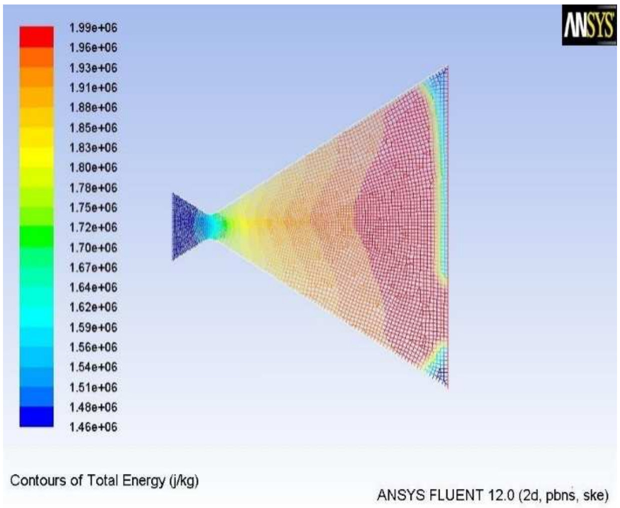

Figure 4.12: Contours of Total Energy

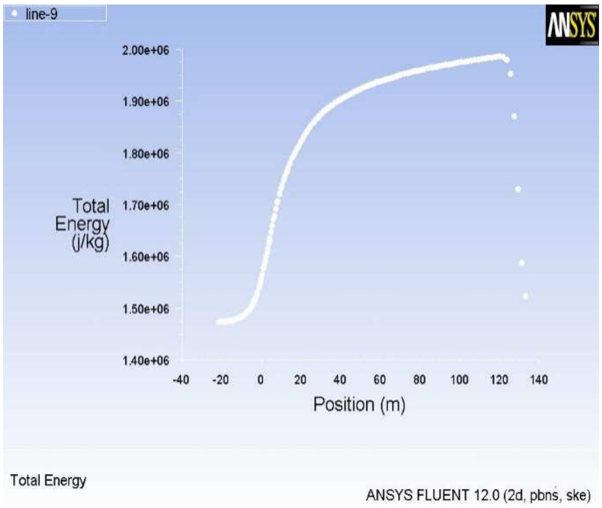

Figure 4.13: Total Energy Vs Position

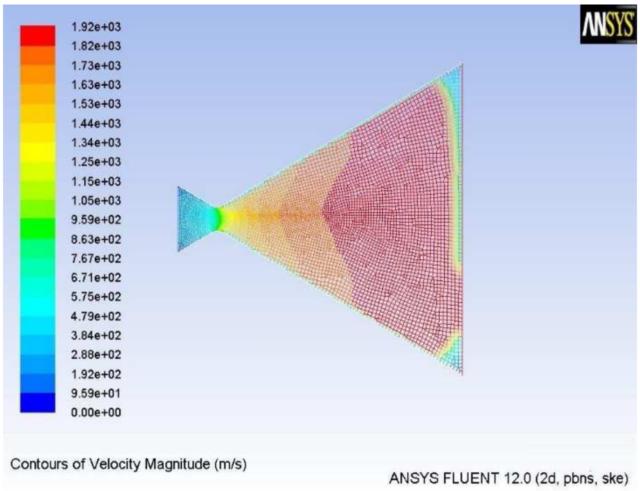

Figure 4.14: Contours of Velocity Magnitude

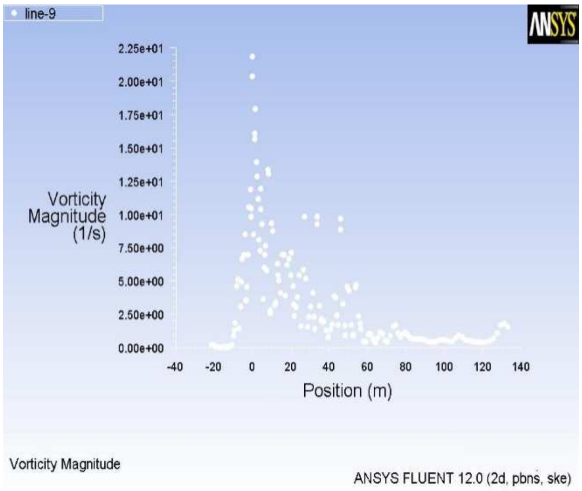

Figure 4.15: Vorticity Magnitude Vs Position

Table 2

Value Name	At 30km	At Sea Level
Thrust	1000N(targeted)	766.05N
Pressure Ratio	0.00057882	0.0045226
Exit Velocity	2539.346 m/s	1984.587 m/s
Critical Pressure	1.1286 MPa	2.068 MPa
Thrust Coefficient	1.78	1.76

From the Above diagrams it is very clear that values obtained at 30km and Sea level are almost similar to the values which obtained during Numerical calculations.

Hence the computational fluid flow analysis at the sea level and 30km altitude are studied and verified for applicable to RCS.

5. CONCLUSIONS

- Computational studies were carried out to get an understanding of the flow fluid of the flow field around Nozzle.
- Improvement in performance of a Rocket with respect to Altitude.
- We can use these types of Nozzles for RCS successfully at 30km altitude.
- Finally, Results obtained by Computational and Numerical methods are compared and got same.

6. SUGGESTIONS TO FUTURE WORK

- It is possible to improve Performance of Nozzle, thus the whole Rocket by using Bell shapes.
- After doing the Structural Analysis by applying the material we can implement this design to the Practical models.
- By implementing this to the Practical models, it’s possible to get more accurate results and thus to Real models.

7. ACKNOWLEDGEMENT

The author would like to acknowledge and express sincere thanks to the technical help and guidance of K. V Reddy, Principal MLRIT&M and Sudhakar Uppalapati, HOD Department of Mech, MLRIT&M

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